



Departamento de Engenharia

Curso de Pós-Graduação *Lato Sensu* em
Formas Alternativas de Energia

CONTROLE DE PROCESSOS APLICADO A SISTEMAS DE PRODUÇÃO DE HIDROGÊNIO E CÉLULAS A COMBUSTÍVEL

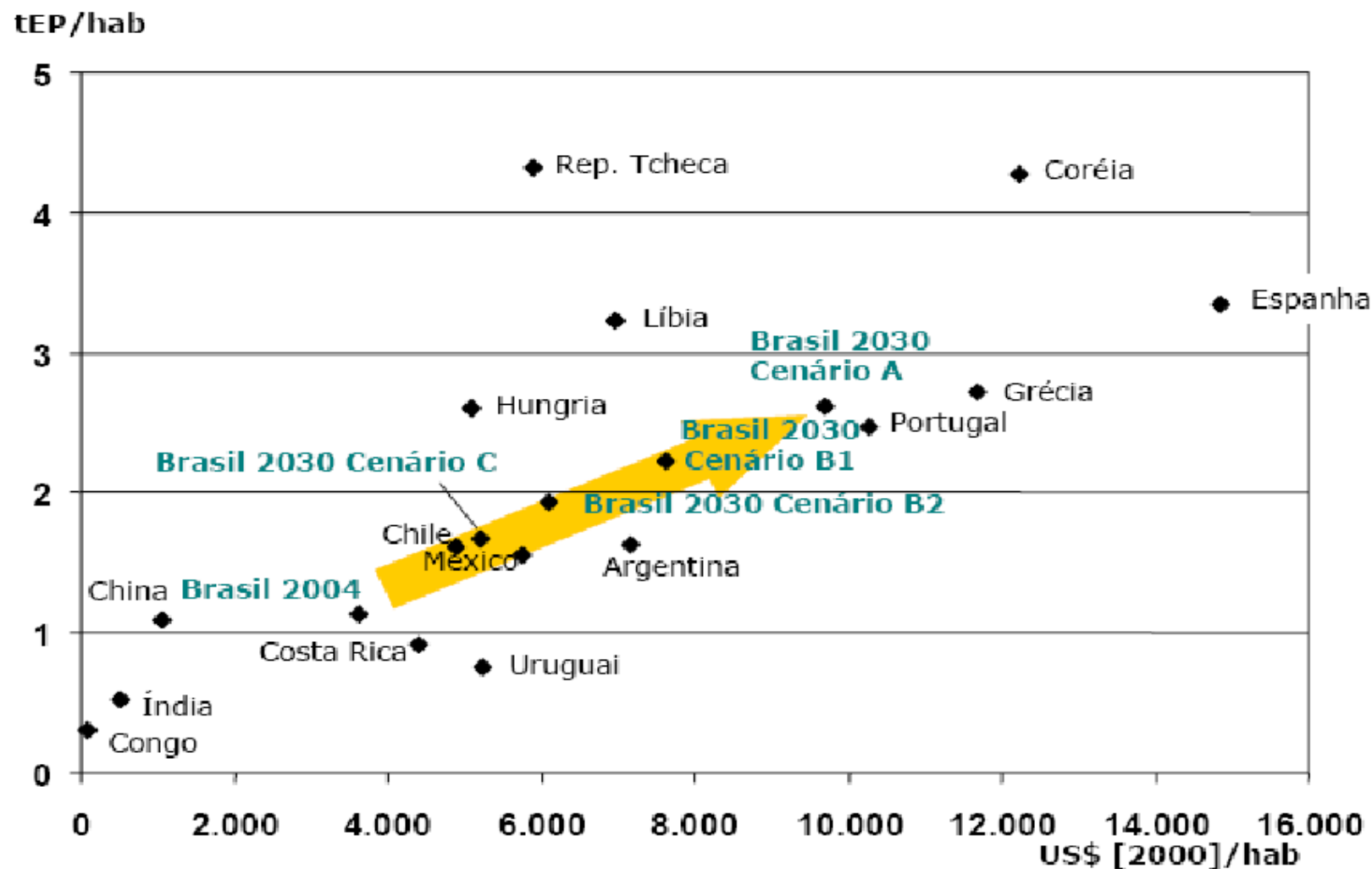
Orientado: CLÁUDIO HOMERO FERREIRA DA SILVA
Orientador: EGBERTO GOMES FRANCO

Roteiro

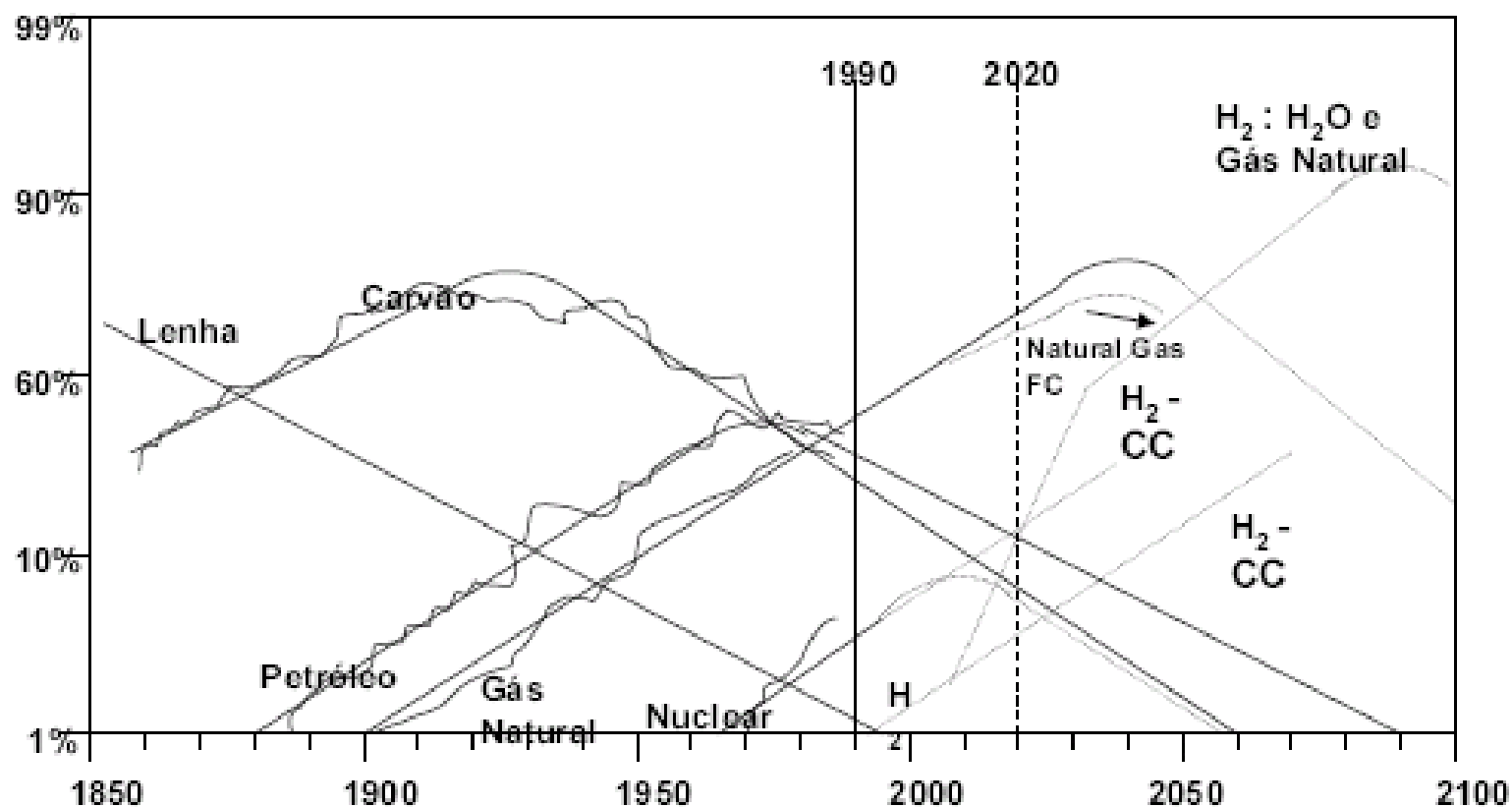
- ✓ Introdução
 - ✓ Revisão: Hidrogênio e as Células a Combustível
 - ✓ Materiais e Métodos: Controle de Processos e Modelagem Dinâmica
 - ✓ Resultados: Simulações
 - ✓ Conclusão
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Introdução

Energia x Desenvolvimento Econômico



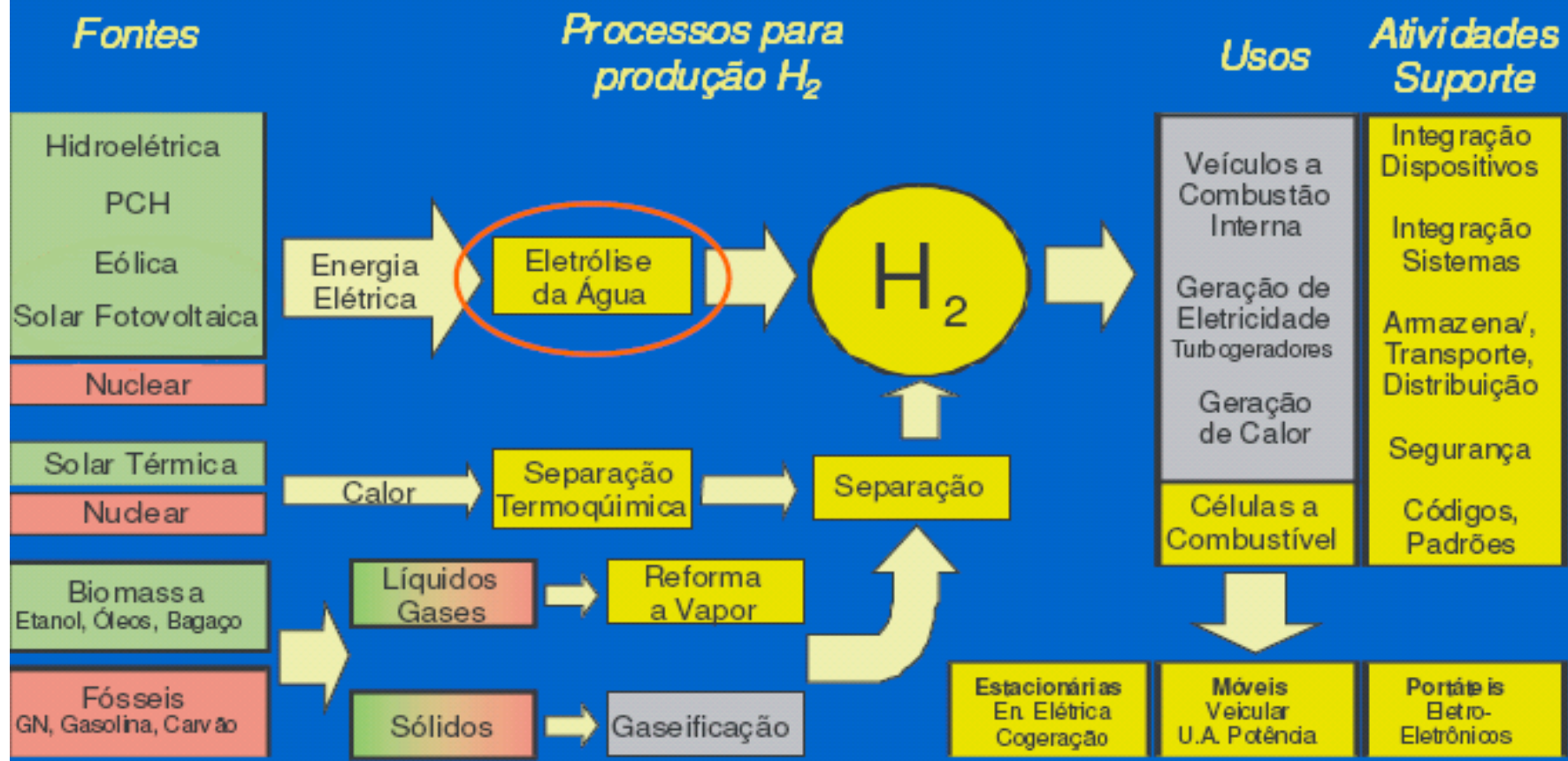
Descarbonização das Fontes de Energia



Fonte: C. Marchetti and N. Nakicenovic. "The dynamics of energy systems and the logistic substitution model" International Institute for Applied Systems Analysis, Austria.

Energia do Futuro: Hidrogênio

Tecnologia do Hidrogênio



Objetivo do Trabalho:

Executar a simulação dinâmica de modelos de processo associados com a produção de hidrogênio e a geração de energia em células a combustível realizando um estudo de análise dinâmica e de aplicação de controle preditivo baseado em modelos.

Revisão: Hidrogênio e as Células a Combustível

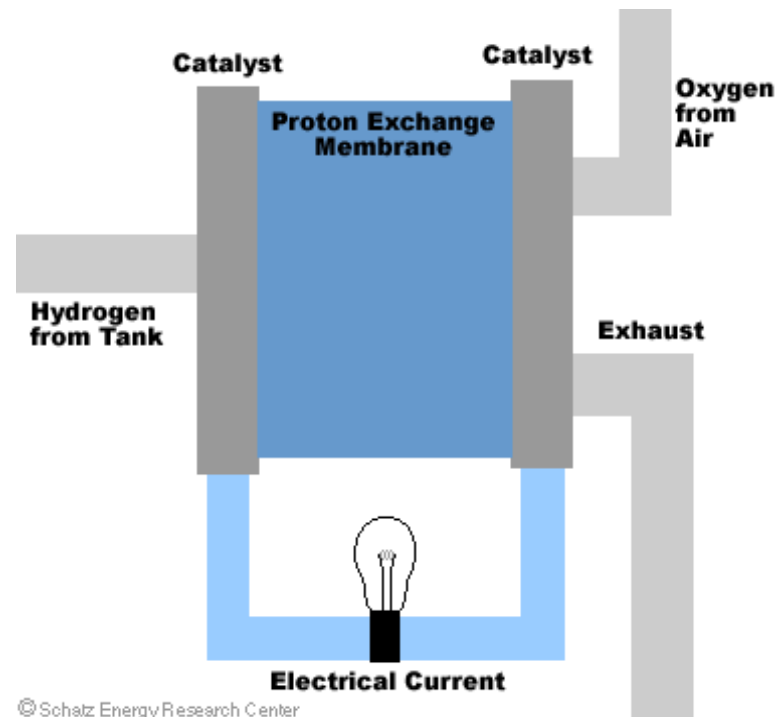
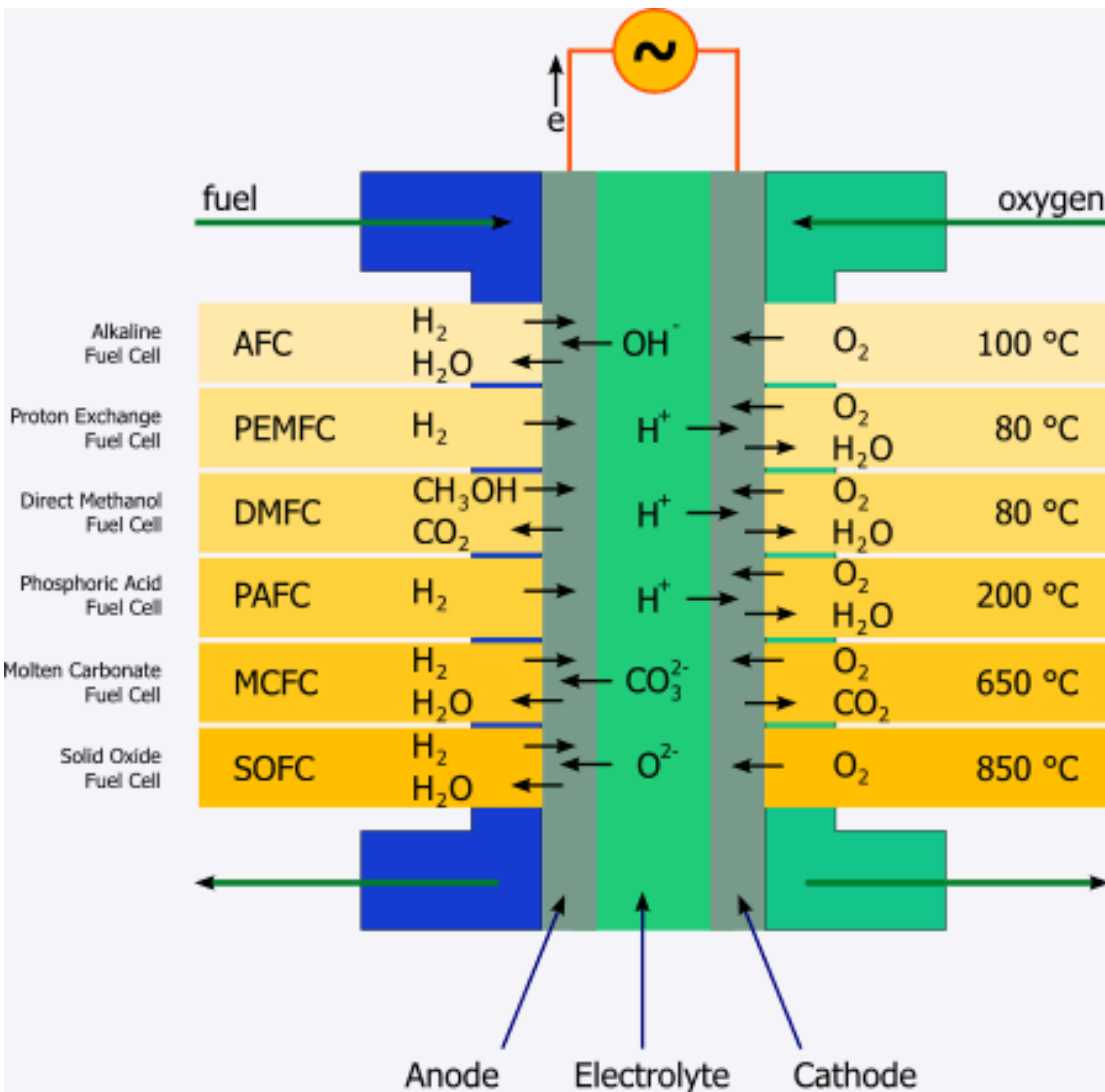
Por que o Hidrogênio???

Abundante e renovável;

- Vetor Energético;
- Democratização;
- Sobrecarga nas fontes;
- Emissão;
- Modularidade;
- Eficiência;
- Silenciosos;
- **Flexibilidade...**

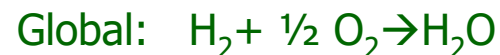
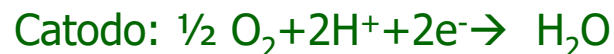
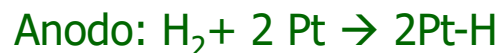


Células a Combustível: Funcionamento



©Schatz Energy Research Center

<http://www.humboldt.edu/~serc/animation.html>



Materiais e Métodos: Controle de Processos e Modelagem Dinâmica

Controle Preditivo baseado em Modelos (MPC)

$$\mathbf{x}(k+1) = \mathbf{A}\mathbf{x}(k) + \mathbf{B}\mathbf{u}(k)$$

$$\mathbf{y}(k) = \mathbf{C}\mathbf{x}(k) + \mathbf{D}\mathbf{u}(k)$$

$$J_k = \min_{\mathbf{u}} \sum_{i=0}^{\infty} \mathbf{y}_{k+i}^T \mathbf{Q} \mathbf{y}_{k+i} + \mathbf{u}_{k+i}^T \mathbf{R} \mathbf{u}_{k+i} + \Delta \mathbf{u}_{k+i}^T \mathbf{S} \Delta \mathbf{u}_{k+i}$$

$$J_k = \min_{\Xi} \Xi^T \mathbf{H} \Xi + 2\Xi^T (\mathbf{G} \mathbf{z}_k - \mathbf{F} \mathbf{u}_{k-1})$$

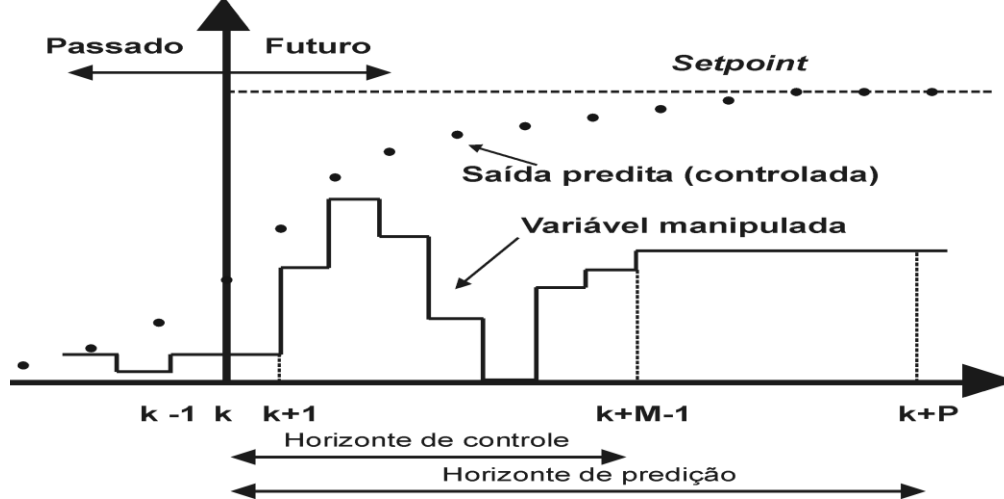
$$\mathbf{H} = \begin{bmatrix} \mathbf{B}^T \bar{\mathbf{Q}} \mathbf{B} + \mathbf{R} + 2\mathbf{S} & \mathbf{B}^T \mathbf{A}^T \bar{\mathbf{Q}} \mathbf{B} - \mathbf{S} & \Lambda & \mathbf{B}^T \mathbf{A}^{T^{N_m-1}} \bar{\mathbf{Q}} \mathbf{B} \\ \mathbf{B}^T \bar{\mathbf{Q}} \mathbf{A} \mathbf{B} - \mathbf{S} & \mathbf{B}^T \bar{\mathbf{Q}} \mathbf{B} + \mathbf{R} + 2\mathbf{S} & \Lambda & \mathbf{B}^T \mathbf{A}^{T^{N_m-2}} \bar{\mathbf{Q}} \mathbf{B} \\ \mathbf{M} & \mathbf{M} & \mathbf{O} & \mathbf{M} \\ \mathbf{B}^T \bar{\mathbf{Q}} \mathbf{A}^{N_m-1} \mathbf{B} & \mathbf{B}^T \bar{\mathbf{Q}} \mathbf{A}^{N_m-2} \mathbf{B} & \Lambda & \mathbf{B}^T \bar{\mathbf{Q}} \mathbf{B} + \mathbf{R} + 2\mathbf{S} \end{bmatrix}$$

$$\mathbf{G} = \begin{bmatrix} \mathbf{B}^T \bar{\mathbf{Q}} \mathbf{A} \\ \mathbf{B}^T \bar{\mathbf{Q}} \mathbf{A}^2 \\ \mathbf{M} \\ \mathbf{B}^T \bar{\mathbf{Q}} \mathbf{A}^{N_m} \end{bmatrix}$$

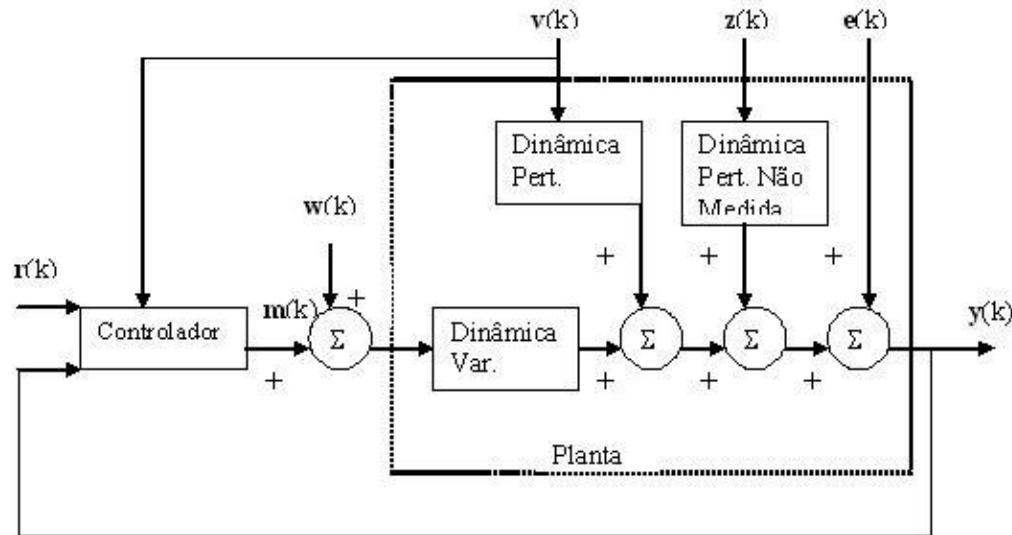
$$\mathbf{F} = \begin{bmatrix} \mathbf{S} \\ \mathbf{0} \\ \mathbf{M} \\ \mathbf{0} \end{bmatrix}$$

MUSKE E RAWLINGS, 1993

Problema de otimização no tempo “k”



Algoritmo implementado (Matlab®)



$$J = \max_{\mathbf{v}(k)} \left\{ \mathbf{a}^T(k) \mathbf{v}(k) - \frac{1}{2} \mathbf{v}(k)^T \mathbf{B}_{\text{MPC}} \mathbf{v}(k) \right\}$$

$$\mathbf{A}_{\text{MPC}}\mathbf{v}(\mathbf{k}) \leq \mathbf{b}(\mathbf{k})$$

$$\mathbf{a}(k) = \mathbf{H}^T \mathbf{Q}_{\text{MPC}} [\boldsymbol{\Psi}_r(k) - \mathbf{Y}_r \mathbf{x}(k|k-1) - \mathbf{Y}_v \mathbf{v}(k) - \mathbf{Y}_d \mathbf{d}(k|k)] + \mathbf{R}_\Delta^T \mathbf{R}_{\text{MPC}} \boldsymbol{\delta}(k) - \mathbf{B}^T \mathbf{v}(k)$$

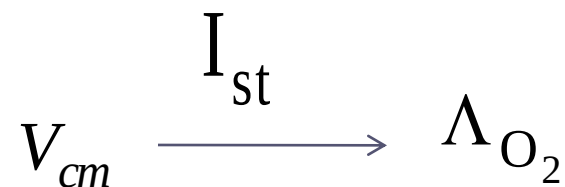
$$\mathbf{B}_{\text{MPC}} = \mathbf{H}^T \mathbf{Q}_{\text{MPC}} \mathbf{H} + \mathbf{R}_{\Delta}^T \mathbf{R}_{\text{MPC}} \mathbf{R}_{\Delta}$$

$$\mathbf{b}(\mathbf{k}) = \begin{bmatrix} \boldsymbol{\mu}_{\max}(\mathbf{k}) - \boldsymbol{\mu}_{\min}(\mathbf{k}) \\ \Delta \boldsymbol{\mu}_{\max}(\mathbf{k}) + \boldsymbol{\delta}(\mathbf{k}) - \mathbf{R}_{\Delta} \boldsymbol{\mu}_{\min}(\mathbf{k}) \\ \Delta \boldsymbol{\mu}_{\max}(\mathbf{k}) + \boldsymbol{\delta}(\mathbf{k}) + \mathbf{R}_{\Delta} \boldsymbol{\mu}_{\min}(\mathbf{k}) \\ -\boldsymbol{\Psi}_{\min}(\mathbf{k}) + \mathbf{H} \boldsymbol{\mu}_{\min}(\mathbf{k}) + \mathbf{Y}_x \hat{\mathbf{x}}(\mathbf{k} | \mathbf{k} - 1) + \mathbf{Y}_v \mathbf{v}(\mathbf{k}) + \mathbf{Y}_d \hat{\mathbf{d}}(\mathbf{k} | \mathbf{k}) \\ \boldsymbol{\Psi}_{\max}(\mathbf{k}) - \mathbf{H} \boldsymbol{\mu}_{\min}(\mathbf{k}) + \mathbf{Y}_x \hat{\mathbf{x}}(\mathbf{k} | \mathbf{k} - 1) + \mathbf{Y}_v \mathbf{v}(\mathbf{k}) + \mathbf{Y}_d \hat{\mathbf{d}}(\mathbf{k} | \mathbf{k}) \end{bmatrix} \quad \mathbf{A}_{\text{MPC}} = \begin{bmatrix} \mathbf{I} \\ \mathbf{R}_{\Delta} \\ -\mathbf{R}_{\Delta} \\ -\mathbf{H} \\ \mathbf{H} \end{bmatrix}$$

$$\begin{bmatrix} -\mathbf{B}_{\text{MPC}} & \mathbf{0} & \mathbf{I} & -\mathbf{A}_{\text{MPC}}^{\text{T}} \\ \mathbf{A}_{\text{MPC}} & \mathbf{I} & \mathbf{0} & \mathbf{0} \end{bmatrix} \begin{bmatrix} \mathbf{v}(\mathbf{k}) \\ \boldsymbol{\zeta}(\mathbf{k}) \\ \boldsymbol{\lambda}_{\text{v}}(\mathbf{k}) \\ \boldsymbol{\lambda}_{\boldsymbol{\zeta}}(\mathbf{k}) \end{bmatrix} = \begin{bmatrix} -\mathbf{a}(\mathbf{k}) \\ \mathbf{b}(\mathbf{k}) \end{bmatrix}$$

Modelo I: CaC - SISO

$$\mathbf{x} = (1,961 \quad 0,5692 \quad 12,92 \quad 78,02 \quad 2,148 \quad 38,544 \quad 1,061 \quad 1,753 \quad)^T$$



$$I_{st} = 191A$$

$$V_{cm} = 163,7V$$

$$\mathbf{x} = (m_{O_2,ca} \quad m_{H_2,an} \quad M_{N_2,ca} \quad \omega_{cp} \quad P_{sm} \quad m_{sm} \quad m_{vap,an} \quad P_{om} \quad m_{vap,ca})^T$$

$$\mathbf{A} = \begin{pmatrix} -12,68 & 0 & -10,94 & 0 & 83,80 & 0 & 0 & 23,99 \\ 0 & -412,8 & 0 & 0 & 133,6 & 0 & -46,19 & 0 \\ -37,45 & 0 & -46,29 & 0 & 275,8 & 0 & 0 & 157,8 \\ 0 & 0 & 0 & -14,52 & 143,1 & 0 & 0 & 0 \\ 2,597 & 0 & 2,97 & 0,3834 & -37,67 & 0,0990 & 0 & 0 \\ 33,28 & 0 & 38,03 & 4,826 & -467,3 & 0 & 0 & 0 \\ 0 & -198 & 0 & 0 & 62,57 & 0 & -78,33 & 0 \\ 4,047 & 0 & 4,623 & 0 & 0 & 0 & 0 & -50,47 \end{pmatrix}$$

$$\mathbf{B}^T = (0 \quad 0 \quad 0 \quad 3,509 \quad 0 \quad 0 \quad 0 \quad 0)^T$$

$$\mathbf{C} = (-1,273 \quad 0 \quad -1,454 \quad 0 \quad 13,89 \quad 0 \quad 0 \quad 0)$$

$$\mathbf{D} = (0)$$

Modelo II: Reformador - MIMO

$$\mathbf{x} = (T_{CPOX} \quad P_{H_2,an} \quad P_{an} \quad P_{hex} \quad \omega_{blo} \quad P_{HDS} \quad P_{CH_4,mix} \quad P_{air,mix} \quad P_{H_2,wrox} \quad P_{wrox})^T$$

$$\mathbf{A} = \begin{pmatrix} -0,074 & 0 & 0 & 0 & 0 & 0 & -3,53 & 1,0748 & 0 & 1E-6 \\ 0 & -1,468 & -25,3 & 0 & 0 & 0 & 0 & 0 & 2,5582 & 13,911 \\ 0 & 0 & -156 & 0 & 0 & 0 & 0 & 0 & 0 & 33,586 \\ 0 & 0 & 0 & -124,5 & 212,63 & 0 & 112,69 & 112,69 & 0 & 0 \\ 0 & 0 & 0 & 0 & -3,333 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -32,43 & 32,304 & 32,304 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 331,8 & -344 & -341 & 0 & 9,9042 \\ 0 & 0 & 0 & 221,97 & 0 & 0 & -253,2 & -254,9 & 0 & 32,526 \\ 0 & 0 & 2,03454 & 0 & 0 & 0 & 1,8309 & 1,214 & -0,358 & -3,304 \\ 0,0188 & 0 & 8,1642 & 0 & 0 & 0 & 5,6043 & 5,3994 & 0 & -13,61 \end{pmatrix}$$

$$\mathbf{B}^T = \begin{pmatrix} 0 & 0 & 0 & 0 & 0,12 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0,1834 & 0 & 0 & 0 & 0 \end{pmatrix}^T$$

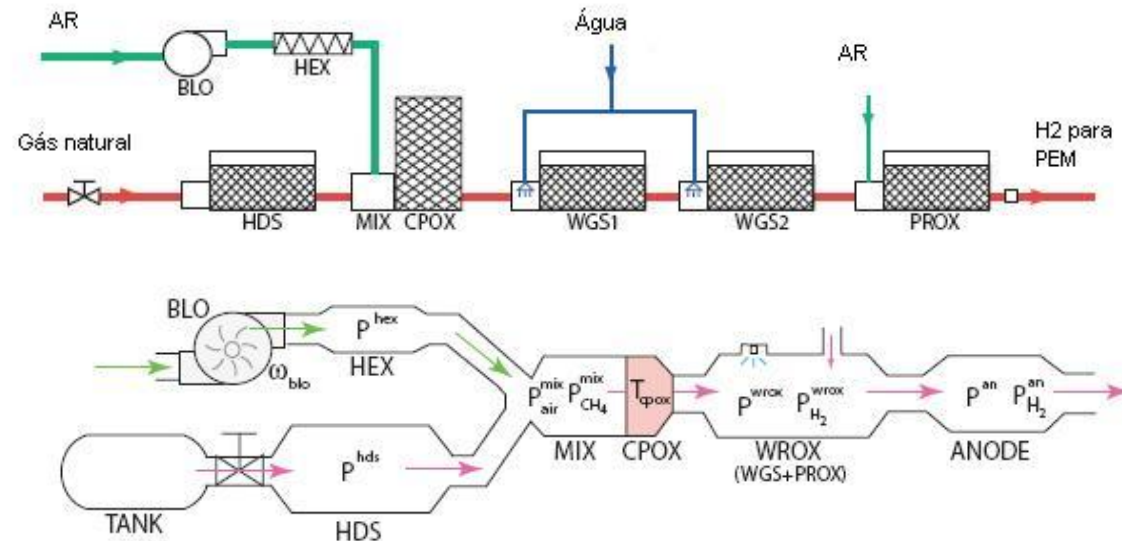
$$\mathbf{C} = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0,994 & -0,088 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

$$\mathbf{D} = \begin{pmatrix} 0 & 0 \\ 0 & 0 \end{pmatrix}$$

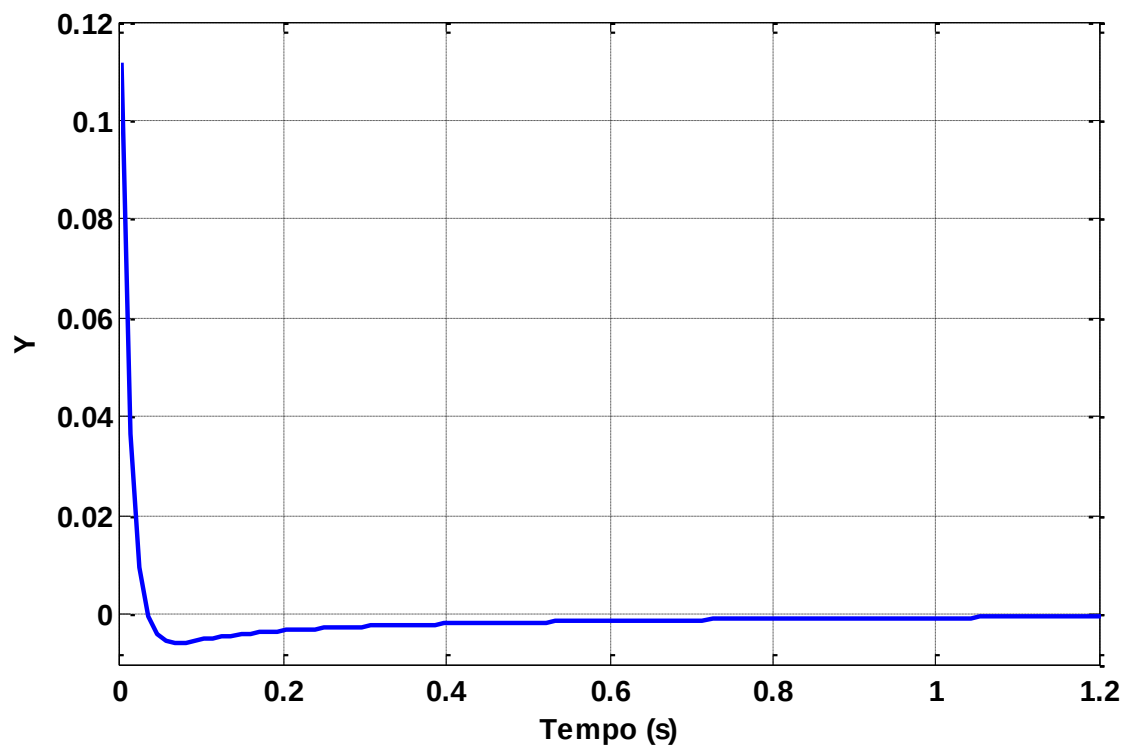
$$\mathbf{u} = (u_{blo} \quad u_{valve})^T$$



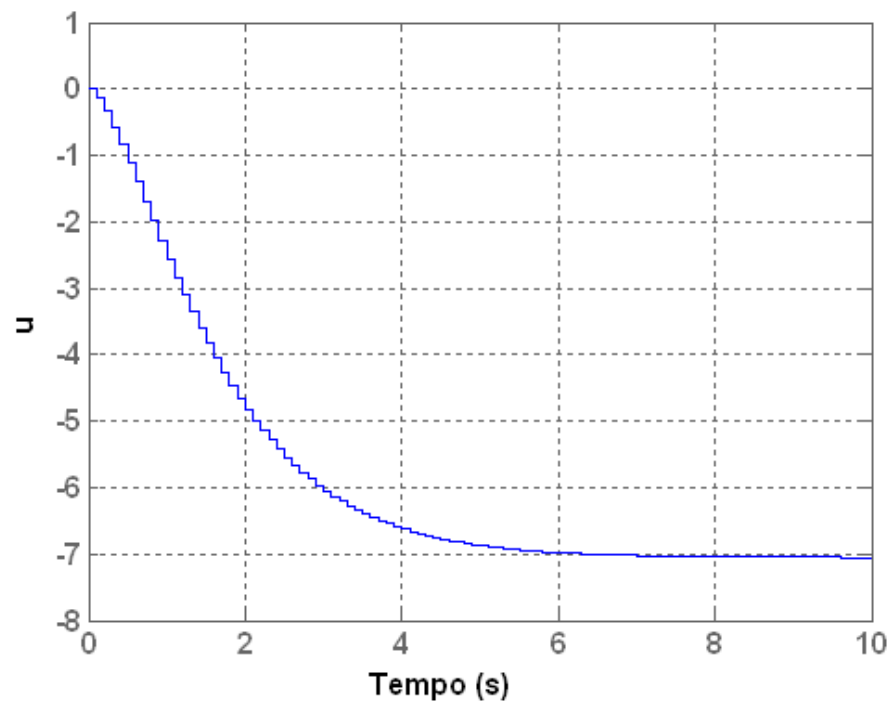
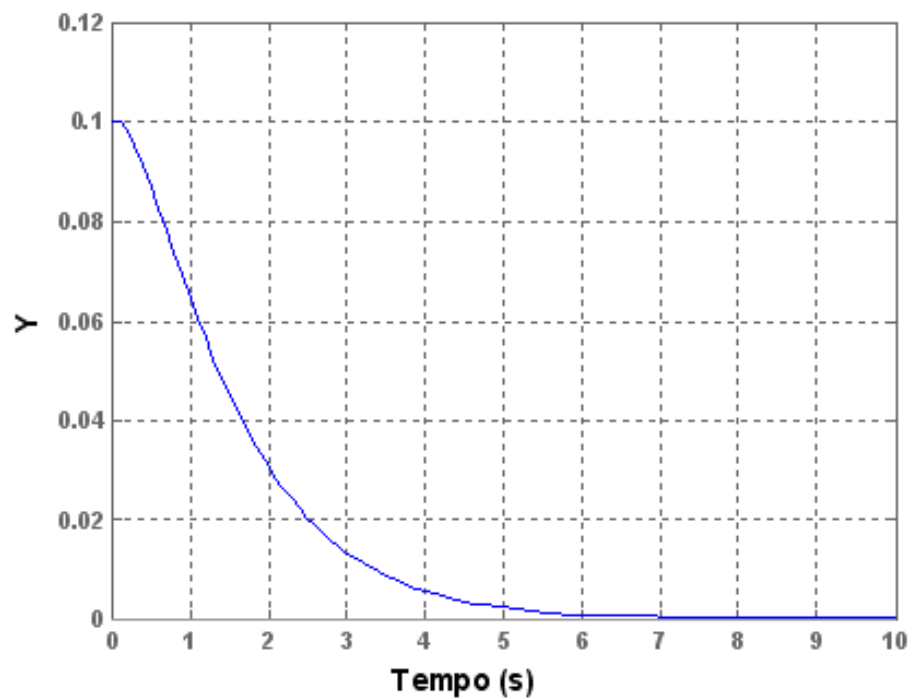
$$\mathbf{y} = (T_{CPOX} \quad y_{H_2,an})$$



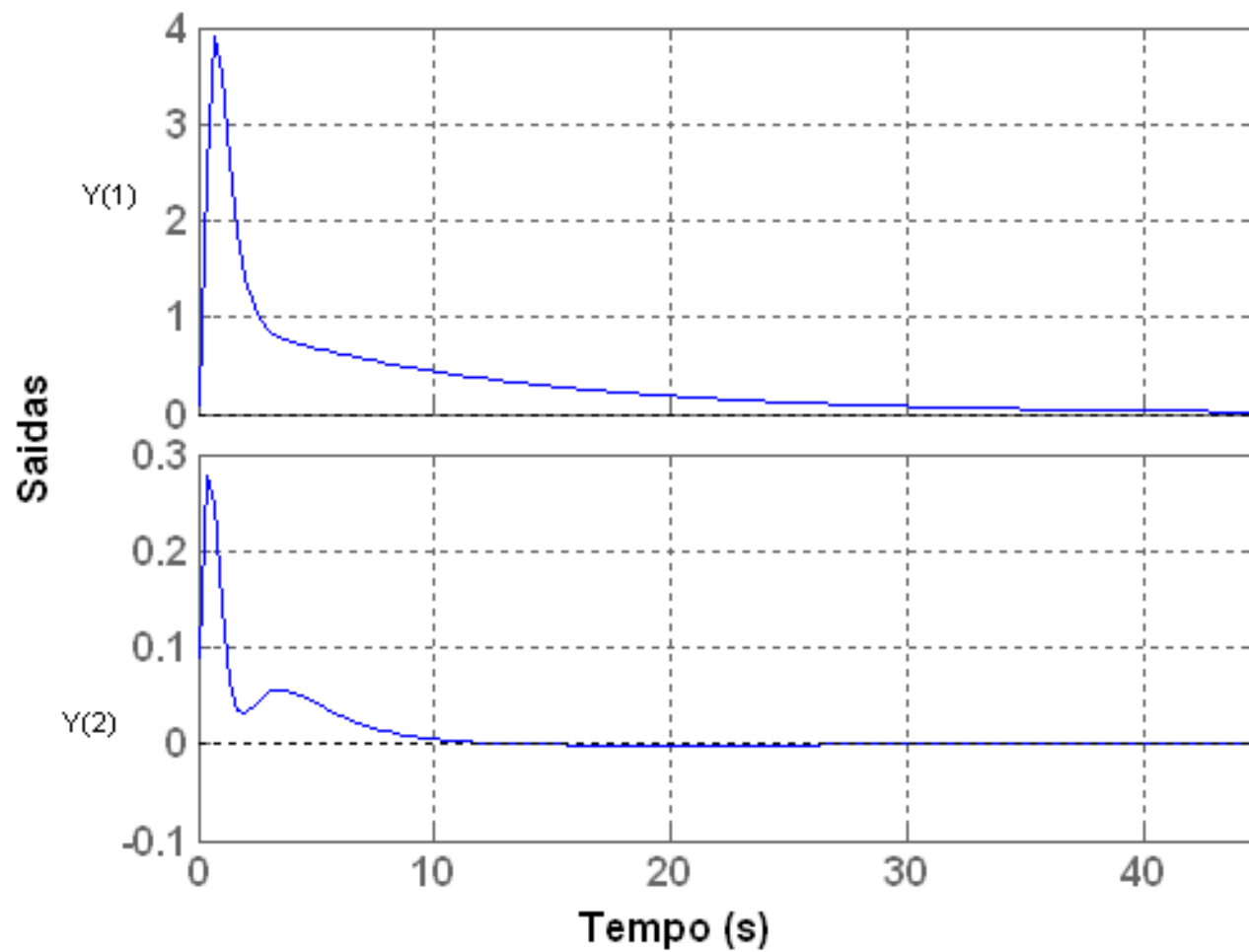
Malha Aberta com Perturbação – Modelo I



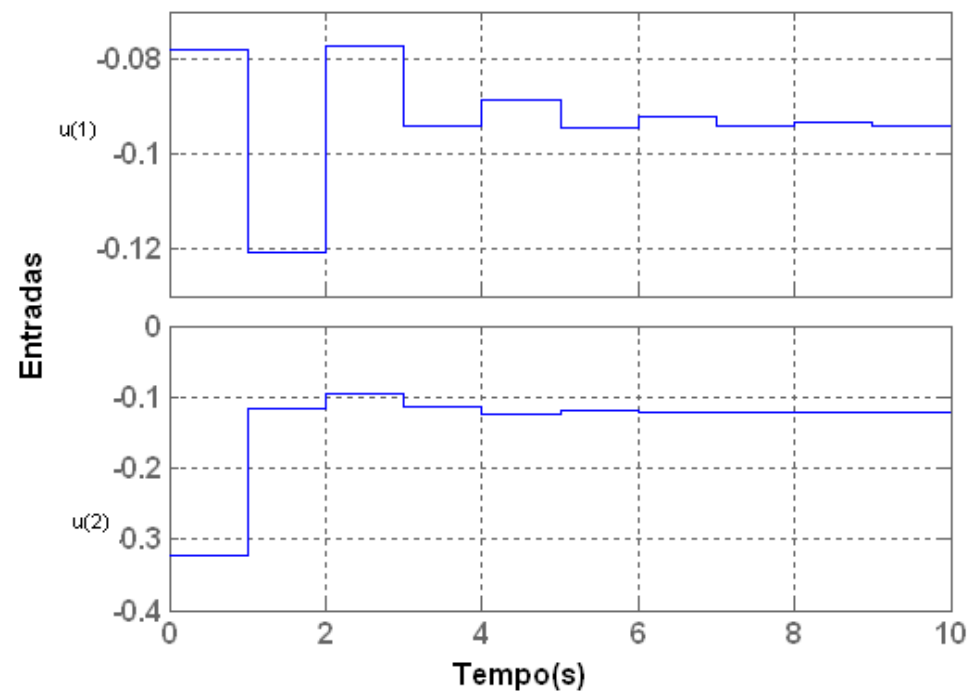
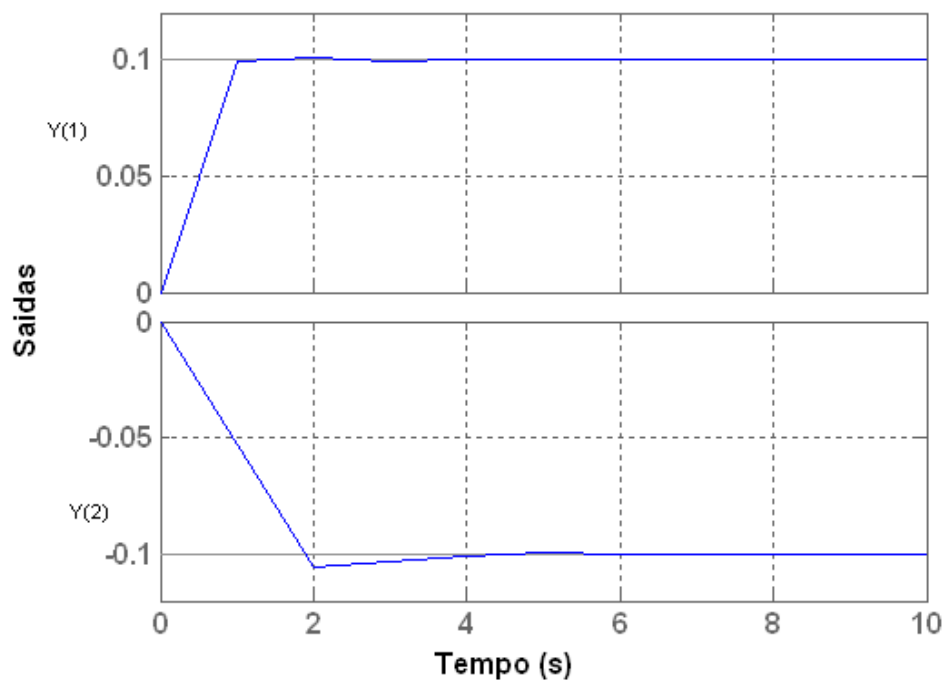
Malha Fechada/Problema Regulador – Modelo I



Malha Aberta – Modelo II



Malha Fechada/Problema Servo – Modelo II



Conclusão:

- ✓ Poucos modelos disponíveis na literatura;
- ✓ Estágios iniciais do desenvolvimento tecnológico no Brasil com poucos estudos em MSCP;
- ✓ Selecionados 2 modelos na literatura: SISO (CaC) e MIMO (Reformador);
- ✓ Aplicado estudo de controle e MPC;
- ✓ Resultados das Simulações: satisfatório do ponto de vista de CP;
- ✓ Sugestões para trabalhos futuros:...

O desenvolvimento da tecnologia das células a combustível se mantém como uma grande expectativa para o futuro da energia, sendo promissora no suprimento energético com baixos custos ambientais.

Obrigado!
